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Pulsars and the Warp of the Galaxy

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Abstract. This paper studies the asymmetries of pulsar distributions relative to the Galactic plane in various Galactic longitudes. It is shown that the observed asymmetric distribution may be explained by the warped and flaring (i.e. increase of scale-height at the peripheries of the Galaxy) structure of the Galaxy. At the peripheries of the Galaxy, the amplitude of the warp, derived from these data, may be as high as $\sim$1 kpc. The scale-height of the pulsar distribution increases exponentially from $\sim$0.5 kpc to $\sim$1 kpc while increasing the galactocentric distance from 5 kpc to 15 kpc. The warp and flare parameters derived from the pulsar data are compared with the stellar and gaseous warp and flare parameters of the Galaxy.

1 Introduction

The existence of a Galactic warp has been known since the first radio surveys of the Galaxy (Burton 1988). Furthermore, it was shown that the distribution of various Galactic components at the peripheries of the Galaxy also shows a flaring structure; i.e., growth of scale-height with increasing Galactic radius. Subsequently, the warped and flaring structure of the Galaxy was studied for young OB stars and old stellar components of the Galaxy, as well as for the Galactic dust emission at $240\,\mu$m (e.g. Alard 2000; Drimmel et al. 1999; Drimmel & Sperge 2001; López-Corredoira et al. 2002a).

The stability and the precise shape and nature of the Galactic warp, however, still remain unclear. The Large Magellanic Cloud, the Sagittarius dwarf galaxy and intergalactic accretion are considered as possible sources of generating Galactic warps (see for example García-Ruiz et al. 2002; Tsuchiya 2002; López-Corredoira et al. 2002b; and Bailin 2003).

It is generally accepted that the progenitors of pulsars are young OB stars, and if their Galactic distributions show warped structure (Drimmel et al. 1999), then the distribution of pulsars also must reveal a similar structure. As objects observable from large distances, pulsars may be more appropriate to study the warped and flaring structure of the Galaxy.

The recent high-frequency, sensitive Parkes Multibeam Pulsar Surveys (PMPS) (Manchester et al. 2001; Morris et al. 2002; and Kramer et al. 2003) revealed many more distant pulsars with high Dispersion Measures (DM). These and all other available observational data of pulsars are collected in new ATNF Pulsar Catalogue (Manchester et al. 2002). The warp and flare of the Galaxy may be estimated analyzing the longitude and latitude distribution of pulsars from this catalogue.

However, warp and flare are more pronounced at distances larger than 10 kpc from the Galactic center and from the Sun. Unfortunately, at present, the number of observable pulsars at these distances is rather small. Probably, more precise estimates of the warp and flare parameters may be possible when a greater number of pulsars will be detected at the peripheries of the Galaxy. However, preliminary studies of warp and flare may be done with the data already available, which is presented in this contribution. Furthermore, warped and flaring structures of the Galactic plane may be used in future to attain a more detailed modeling of the Galactic electron distribution and more precise estimates of distances for some distant pulsars.

2 Observed Data and Warped Disc Model of the Galaxy

Yusifov & Küçük (this volume, YK2003 hereafter) have studied the Galactic distribution and the luminosity function of pulsars on the basis of new ATNF catalogue of 1412 pulsars (Manchester et
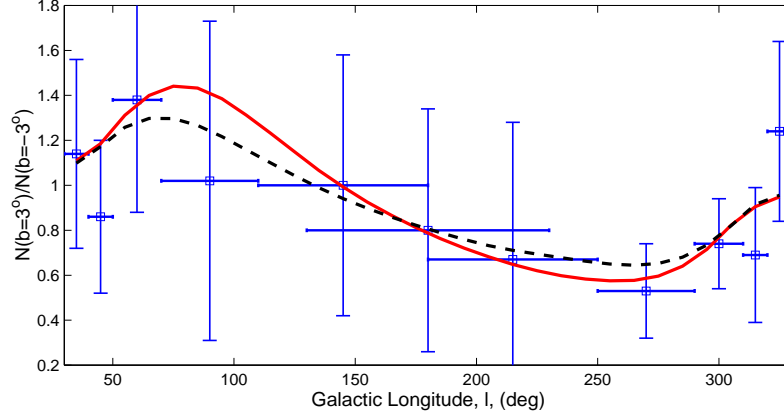
Fig. 1. Ratio of positive counts of pulsars to negative ones with corresponding errors. Horizontal bars correspond to the width of the considered longitude intervals. Dashed and solid lines correspond to the best-fitting models with and without taking into account data points at longitude $l = 90°$.

al. 2002). We have used here the results of this study to derive the warp and flare parameters of the Galaxy.

The estimates of the parameters of the warp and flare were made by the method described in López-Corredoira et al. (2002a), with some modifications. For this study we select "normal" pulsars at Galactic latitudes $|l| \leq 5°$, excluding binary and recycled ($\dot{P} < 10^{-17}$ s/s), globular cluster and extragalactic pulsars. We found the ratio of the cumulative number of pulsars above and below the Galactic plane at various Galactic longitudes centered at $b = \pm 3°$; the results with the corresponding error bars are plotted in Fig. 1. The errors in Fig. 1 are estimated assuming that the observed cumulative numbers follow the Poisson distribution. In order to see the warping effect clearly, pulsars located within $r \leq 1$ kpc from the Sun were excluded from consideration.

The number of pulsars at various longitudes varies dramatically, and in order to gather a statistically significant number of pulsars, as is seen from Fig. 1, the longitude width of the interval was chosen to be variable. The latitude width of the intervals, which is centered on $b = \pm 3°$, was $\Delta b = 4°$.

In spite of the existence of large error bars, the plot clearly shows a sinusoidal behavior. If the warped structure were absent, the ratio of counts should be nearly the same for all Galactic longitudes. A similar behavior may be easily explained by the warp of the Galactic plane.

The parameters of the warp will be found from Fig. 1, fitting the observed ratios with the modeled ones. The stellar statistic equation has the form:

$$A(m) = \int_0^\infty r^2 D(r) \phi(M) dr \; , \tag{1}$$

where $A(m)$ is the number of stars per unit area of solid angle ω at m in interval dm, $\phi(M)$ is the luminosity function and $D(r)$ is the stellar density. Converting this relation to the pulsar data for our purpose, we obtain:

$$N(l, b) = \omega \int_{r_2}^{r_1} N_0(l, b, r) \rho[R(l, b, r), z(l, b, r)] r^2 dr \; , \tag{2}$$

where r and R are the distances from the Sun and the Galactic center, ρ is the space density and

$$N_0(l, b, r) = \int_{S_0 r^2}^{L_{\max}} \Phi(L) \frac{dL}{L} \tag{3}$$

is the local surface density of pulsars at distance r from the Sun. S_0 is the minimum detectable flux density, and $L_{\max} = 10^4$ mJy kpc^2 is the maximum luminosity of pulsars at 1400 MHz. For the

minimum detectable flux density we assume a derived value of $S_0 = 0.07$ mJy from YK2003. The Galactic distribution and luminosity function of pulsars accepted from YK2003 have the form:

$$\sigma(R) = C \left(\frac{R}{R_\odot} \right)^a \exp \left(-b \frac{R - R_\odot}{R_\odot} \right) , \qquad (4)$$

where $\sigma(R)$ is the surface density of pulsars with parameters $C = 40$ kpc^{-2}, $a = 1.12$, $b = 3.2$, and $R_\odot = 8.5$ kpc is Sun–Galactic center distance and

$$\Phi(L) = \frac{A_L}{\sigma_L \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\log L - \log L_O}{\sigma_L} \right)^2 \right] , \qquad (5)$$

where $A_L = 67, \sigma_L = 1.21$ and $\log L_O = -1.64$. The space distribution then has the form:

$$\rho(l, b, r) = N_0(l, b, r) \left(\frac{R}{R_\odot} \right)^a \exp \left(-b \frac{R - R_\odot}{R_\odot} \right) \exp \left(-\frac{|z|}{h_z(R)} \right) \frac{h_z(R)}{h_z(R_\odot)} , \qquad (6)$$

where $h_z(R)$ is the scale-height of pulsar distributions. In order to study flaring of pulsar distributions in the model is included exponentially increasing scale-height by the relation:

$$h_z(R) = h_z(R_\odot) \exp \left(\frac{R - R_\odot}{h_{R,flare}} \right) , \qquad (7)$$

where $h_z(R_\odot)$ and $h_{R,flare}$ are free parameters. The factor $\frac{h_z(R)}{h_z(R_\odot)}$ in Eq. (6) is normalized due to the variable scale-height of $h_z(R)$.

In order to take the warping structure into account in relation (6), $|z|$ must be replaced by $|z - Z_w|$, where the function $Z_w(R, \phi)$ describes the vertical displacement of the warp. From the early studies of H I it is known that the warping structure of the galaxy is asymmetric (see for example Burton (1988)), and at the galactocentric distances $R > 14$ kpc the southern warp becomes constant with height (see Fig. 2). For this reason, for the warped model of the Galactic plane, we include an additional free parameter, as the galactocentric radius R_{WS}, from which the southern warp becomes constant, and correspondingly $Z_w(R, \phi)$ is calculated by the relation:

$$Z_w(R, \phi) = \begin{cases} C_W (R - R_W)^{b_w} \sin(\phi - \phi_W) + 15, & \text{for } R \leq R_{WS} , \\ C_W (R_{WS} - R_W)^{b_w} \sin(\phi - \phi_W) + 15, & \text{for } R > R_{WS} . \end{cases} \qquad (8)$$

Here, R_W is the galactocentric radius, from which the warp starts (for $R < R_W$, $Z_w(R, \phi) = 0$), ϕ is the galactocentric angle taken in the direction of Galactic rotation with the Sun lying along $\phi = 0°$.
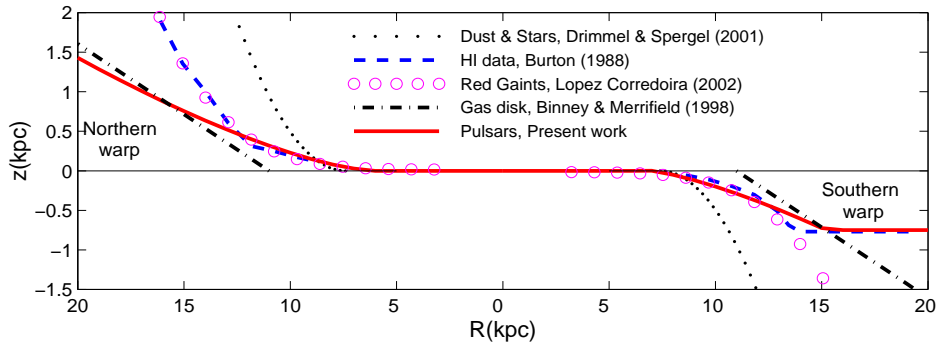

Fig. 2. Comparison of the maximum of amplitudes of the various Galactic warps models, plotted as a function of galactocentric distance. Data of all models were converted to $R_\odot = 8.5$ kpc.
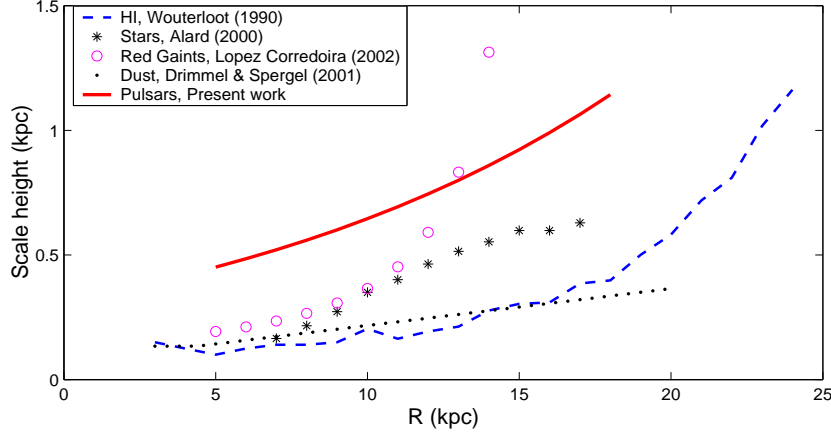
Fig. 3. Comparison of the scale-height variations of various Galactic components plotted as a function of distance to the Galactic center.

3   Results and Discussion

Using relations (2)–(8) we have fitted the observational data in Fig. 1 by the least mean square method and estimated the warp and flare parameters in Eqs. (7) and (8). For the best-fitting parameters we obtain:

$$h_z(R_\odot)\text{=580 pc,} \quad h_{R,flare}\text{=14 kpc;} \tag{9}$$

and

$$C_W\text{=37,} \quad R_W\text{=6.5 kpc,} \quad b_w\text{=1.4,} \quad \phi_w\text{=14.5}^\circ \quad \text{and} \quad R_{WS}\text{=15.2 kpc} \tag{10}$$

The results of fitting by these parameters are shown by the solid lines in Figs. 1–3. In Figs. 2 and 3 we compared the warp and flare results of our study with similar results of other studies. It is interesting to note that the warp of the galactic disc derived from pulsar data is more closely related to the gas disc warp (Binney & Merrifield 1998; Bailin 2003) than the stellar and dust warps, which are described in López-Corredoira (2002a) and Drimmel & Spergel (2001).

In fitting the observational data in Fig. 1, we used both a symmetric and asymmetric warp. Calculations show that the asymmetric warp better fits the observational data, and the obtained southern asymmetry is very closely related to H I data (see Fig. 2).

We estimated the scale-height of the pulsar distribution ($h_z(R_\odot) = 580$pc) here by quite a different method than that used (e.g. Lyne et al. (1985) and references therein) and it occurred nearly 30% greater than that of earlier estimates (450 pc). The large scale-height of pulsars may be caused by the additional fact of the high-velocity origin of pulsars.

From Fig. 3 it is seen that, as for other components of the Galaxy, the scale-height of the pulsar distribution also increased with increasing galactocentric radius. This increase strongly deviates from the red giant flaring and is nearly parallel to the H I and dust flaring.

From previous studies it was known that the line of nodes or phase angle of the warp (ϕ_w) is $\approx 0^\circ$ (see for example Drimmel & Spergel 2001) or even has a negative value $\approx -5^\circ$ (see for example López-Corredoira et al. 2002). But from fitting pulsar data in Fig. 1 we obtain $\phi_w \approx 15^\circ$ for the phase angle of the warp.

Figure 4 shows the general view of the Galactic plane obtained in this study. There are very few pulsars at distances $R > 15$ kpc, and for this reason the precise values of warping and flaring at these distances are still waiting to be elucidated. Nevertheless, this warping structure of the Galactic plane may be very helpful in distance estimates of some high-DM pulsars. The inclusion of the warping and flaring structure of the Galaxy to the large-scale modeling of the ISM electron distribution may serve as the next step to improve the model.
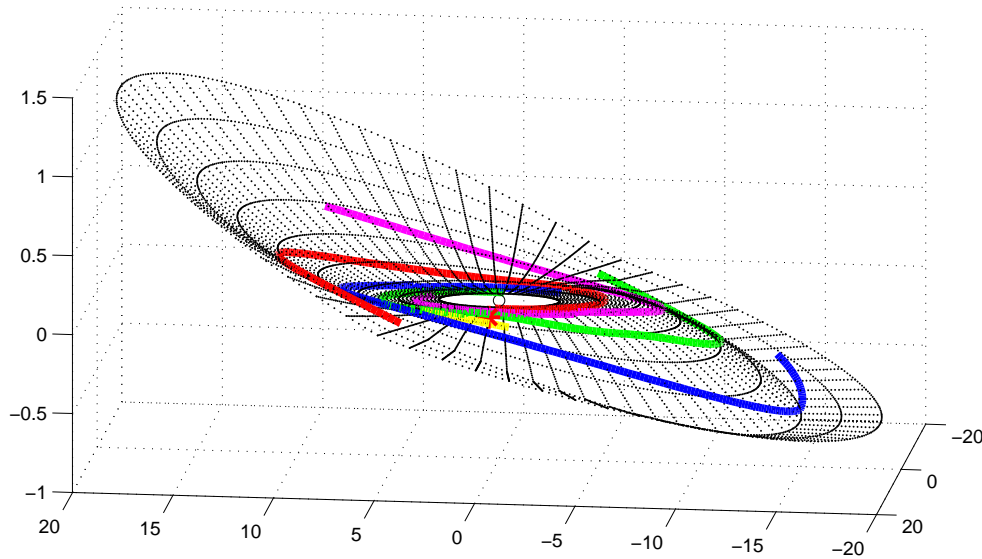
Fig. 4. A schematic 3D view of the Galactic warped plane together with spiral arms from Cordes & Lazio (2002). In order to present a better appearance of the warping structure, the scale in the z direction is considerably increased.

Acknowledgments

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